PROPULSION DIVISION

SUMMARY REPORT

INJECTOR ORIFICE STUDY
APOLLO SERVICE PROPULSION SYSTEM

Prepared Under
Contract NAS 9-6925

Report 6925-S

15 July 1968

AEROJET GENERAL TIRE GENERAL ®

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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INJECTOR ORIFICE STUDY

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For

MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Houston, Texas

25704T

AEROJET-GENERAL CORPORATION

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

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FIGURE LIST

I. INTRODUCTION

The report presented herein is a summary of the work accomplished on the Apollo Service Propulsion System Injector Orifice Study Program (IOS), Contract NAS 9-6925, for the National Aeronautics and Space Administration - Manned Spacecraft Center (NASA/MSC). The period of performance was 7 April 1967 through 31 July 1968. The program goal was to establish a thorough understanding of the hydraulics of short-tube flow and then to apply this understanding to the design and fabrication of an optimized Apollo Service Propulsion System (SPS) injector.

II. STUDY OBJECTIVES

The primary objective of the Injector Orifice Study (IOS) was the development of an optimized injector design for advanced Apollo missions. To achieve this objective the program was organized to include an investigation into the characteristics of injector orifices. The knowledge gained from this investigation was then incorporated into the optimized injector design criteria. Phase I of the two-phase effort was conducted to evaluate injector hydraulic design parameters by means of a review of previous applicable work on short-tube flow, cold-flow testing of selected types of orifices, and establishing injector design criteria.

The Phase II effort consisted of fabrication and test of the injector designed during Phase I.

III. RELATIONSHIP TO OTHER NASA EFFORTS

The IOS program was directly related to the SPS engine program, NAS 9-150, and to any projected use of that engine.

In addition, Contract NAS 9-6698 was awarded to the Houston Research Institute to evaluate certain portions of the work accomplished by Aerojet (AGC) during Phase I of the IOS Program. The results of that study, which are in general agreement with those of AGC, are documented in the Contract NAS 9-6698 Final Report.

A follow-on to the IOS Contract, NAS 9-8285, was awarded to AGC on 28 June 1968.

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The IOS Program was divided into two phases. Phase I consisted of the investigation of the hydraulics of short-tube flow and injector design, and Phase II consisted of injector fabrication and test. These two phases were

IV, Method of Approach and Principal Assumptions (cont.)

in keeping with the basic program philosophy or method of approach, i.e. to obtain a theoretical understanding of the problem prior to committing hardware to fabrication.

Although the nature of the program objectives and the absence of delivery requirements put the program in the research and development category, the level of documentation and quality assurance was more formal than that usually associated with research programs. The contractual inspection provisions were a modified form of NASA Quality Publication 200-3; however, the degree of quality assurance and the method of processing design disclosures, i.e. engineering drawings and specification, closely paralleled those procedures employed by the SPS Program. Consequently, the IOS design could be incorporated into a production program meeting all the requirements of NASA Quality Publication NPC 200-2 with a minimum of additional effort.

The design approach was to optimize the SPS Mod IV injector by incorporating the knowledge gained during the Phase I studies and element flow tests.

The order of precedence for design considerations was:

Hydraulics
Performance
Stability
Compatibility

The resulting design compared to the SPS Mod IV injector is shown in Figure 1, and the rationale employed in developing the various design features is discussed in the following paragraphs.

A. HYDRAULICS

Modifications to the hydraulic circuit included the exclusive use of orifices with contoured inlets and the addition of oxidizer channel cover plates.

The contoured orifices had demonstrated superior flow characteristics during the Phase I injector element tests and the oxidizer channel cover plates were designed to furnish more uniform oxidizer temperature by effectively

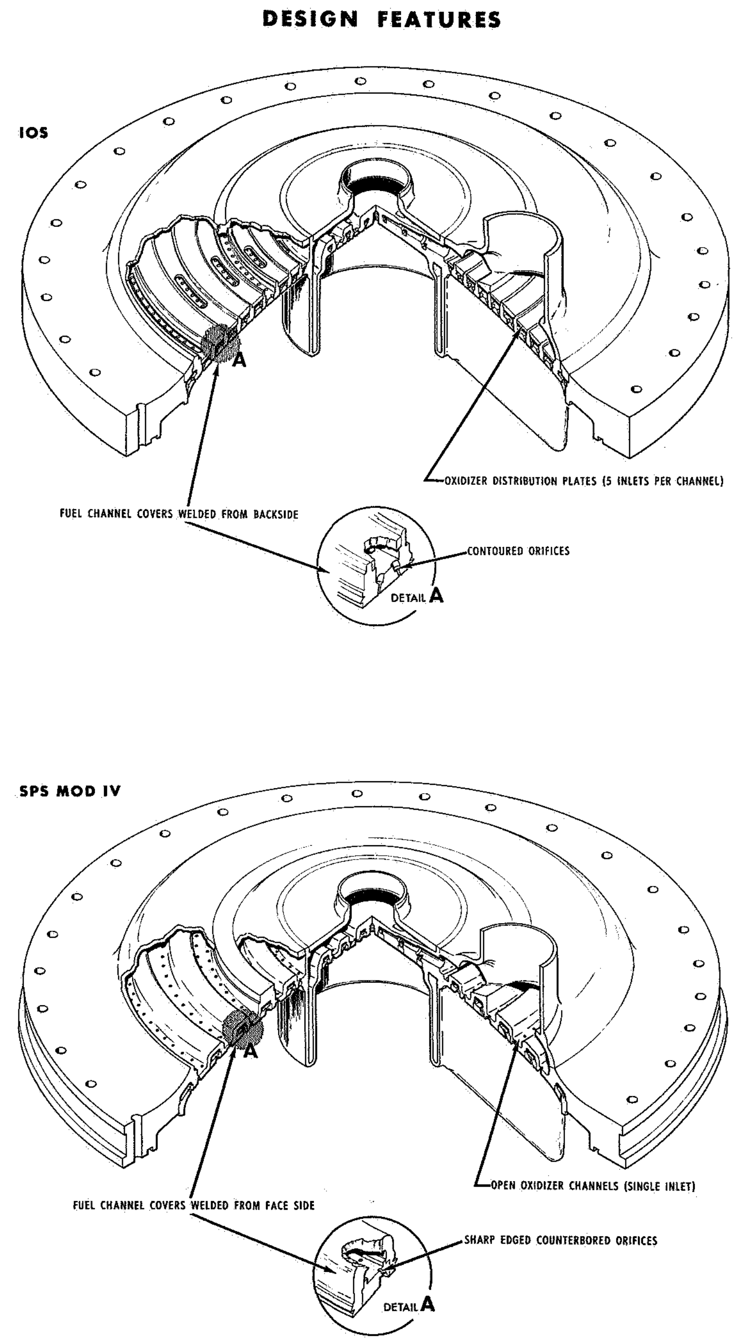

Figure 1. Injector Design Features

IV, A, Hydraulics (cont.)

providing five inlets to each oxidizer channel rather than one. The advantage of multiple inlets is that the temperature rise due to the oxidizer contact with the hot injector face is considerably reduced from inlet to the orifice inlet. More uniform temperature, of course, results in a more uniform mixture ratio.

B. PERFORMANCE

Modifications implemented in the interest of improved performance were based upon the following ground rules.

1. The injector pattern would have an even mixture ratio distribution.

2. The existing row of doublets near the chamber wall would remain radial.

3. The minimum acceptable spray fan overlap for the injector would be on the order of 50%.

4. Compatibility and stability were not to be significantly degraded.

5. The film coolant would be retained at 5% of the total fuel flow.

A pattern was developed (Figure 2) with the objective of meeting these requirements in all respects. It consists of 955 active elements (compared to 585 for the Mod IV) and provides a uniform mixture ratio distribution across the injector face. With the increase in the number of orifices, and the selected element cant angle the total injector has 45% spray overlap versus 14% with the Mod IV. The performance increase expected over the Mod IV configuration was 4 sec of I_s consisting of 2 sec from the increase in spray fan overlap combined with increased vaporization and 2 sec from mixture ratio distribution. This pattern also incorporates element cant angles (measured from a radial line) of 60 degrees.

C. STABILITY

Because experience at Aerojet has been generally that injectors with small orifice sizes tend to be less stable, the stability evaluation was recognized as being extremely critical.

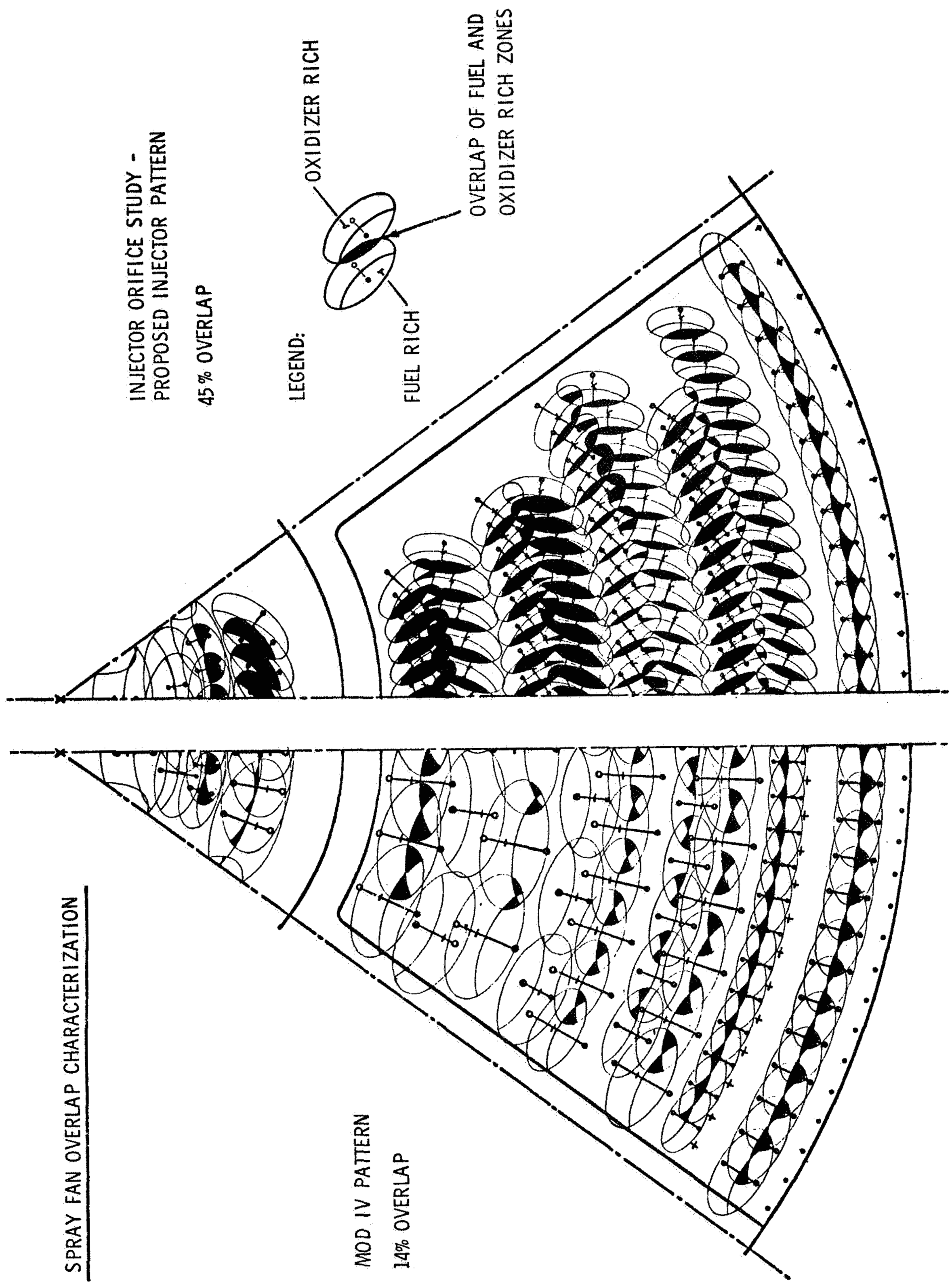

Figure 2. Spray Fan Overlap Characterization

IV, C, Stability (cont.)

To make the IOS injector as stable as possible within the design limitations, several factors were considered in the design stability analysis. A review was made of previous SPS injector test history to establish the limiting orifice size, and a critical evaluation was made of the damping efficiency to be expected from the existing 5-4-4 baffle when combined with the IOS pattern. Other factors considered were the contoured orifices, which would tend to exert a stabilizing influence because of their uniform flow properties; and the effect of the increased spray fan overlap, which was also a stabilizing influence because it minimized the number of pockets available to store energy capable of supporting chamber pressure perturbations. Particular emphasis was placed upon the IOS propellant mass distribution.

Mass injection distribution has proved to be a very powerful stability parameter. It has been used successfully at Aerojet to obtain stability without the use of mechanical damping devices by the elimination of active injection elements near the chamber wall and enlarging the remaining orifices to create a stepped mass injection distribution. This method reduces the quantity of propellant injected at the area of high acoustic pressure within the chamber, thereby reducing the amount of acoustic energy input in phase with the pressure oscillation. Figure 3 shows the mass flow distribution for both the IOS and Mod IV injectors.

D. COMPATIBILITY

The method employed for determination of the compatibility potential of the IOS injector basically consists of allotting a stream tube flow area to each injector element based upon its energy release potential, and then determining graphically the direction of movement of the combustion gases by minimizing interference between the stream tubes. This interference or overlap tends to create high-pressure areas which cause cross winds as the gases flow from the high-pressure areas to low-pressure areas.

A comparison of the Mod IV and the proposed IOS pattern showed that the wall compatibility should be improved for the IOS pattern. However, the rest of the injector pattern indicated more severe dynamic winds moving directly

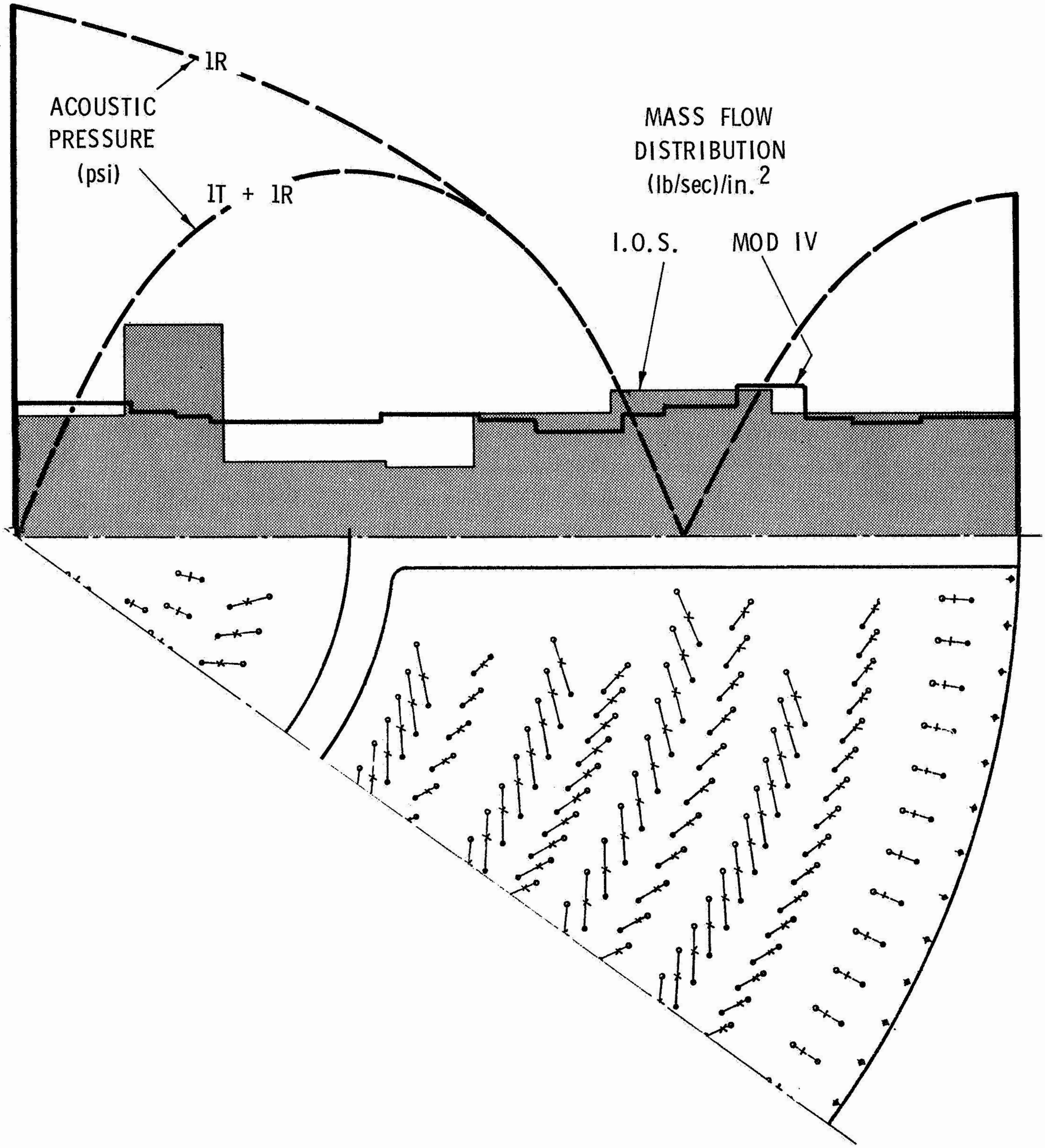

Figure 3. Mass Flow Distribution

IV, D, Compatibility (cont.)

toward the baffles. A review of the Mod IV heat transfer analysis showed the heat flux safety margin to be sufficient to prevent damage.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The basic data generated in the two program phases included the fol-fowing:

A. PHASE I

Publication of a comprehensive literature survey on the subject of orifice flow, listing more than 300 sources of information.

Analysis of the injector element cold-flow tests resulting in the derivation of expressions for the value of C_d for both contoured and sharp-edged orifices over a range of operating parameters.

A comparison of the results of current injector orifice inspection techniques with those obtained by more sophisticated techniques.

Other tasks accomplished during Phase I which also generated data were:

An injector orifice test program encompassing approximately 130 individual tests over a range of operating parameters and propellants.

The design of the IOS injector which involved 30 engineering drawings.

The publication of inspection, fabrication and test plans.

B. PHASE II

The most significant data generated in Phase II are the test results shown in Figure 4. These data indicate (1) the techniques used to increase performance were successful, (2) compatibility techniques were in all probability successful although insufficient firing time has been accumulated to make a definite statement to that effect, and (3) measures taken to provide dynamic stability were unsatisfactory in that both the intermediate (850 cps) and high (7000 cps) instability are present. The intermediate frequency instability is associated with propellant feed system coupling. The high-frequency instability is considerably higher than any previously encountered on the SPS engine and is of a mode beyond the damping capability of the baffles.

TEST NO. 1127-D01-0J	DURATION, SECONDS	Pc, psia	I_s Vac* ϵ = 62.5 sec	MR	COMBUSTION CHAMBER	COMMENTS
-001	5.2	96.8	319 $\pm$ 2	1.63	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-002	5.3	97.7	319 $\pm$ 2	1.59	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-003	5.2	98.0	319 $\pm$ 2	1.60	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-004	5.2	97.3	319 $\pm$ 2	1.82	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-005	5.2	97.8	319 $\pm$ 2	1.40	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-006	5.4	70.8	319 $\pm$ 2	1.57	STEEL	INTERMEDIATE-FREQUENCY INSTABILITY AT 850 cps/1250 cps THROUGHOUT TEST. INCREASED NUMBER OF POPS OBSERVED.
-007	5.4	107.9	319 $\pm$ 2	1.71	STEEL	ROUGH START, STABLE COMBUSTION ($\pm$ 4 psi) INDICATIONS OF SMALL POPS MAX < 25 psi AT RATE 1/sec. GOOD COMPATIBILITY INDICATIONS.
-008	5.2	97.4	319 $\pm$ 2	1.58	STEEL	START TRANSIENT INDUCED HIGH FREQUENCY INSTABILITY DAMPS IN 50 msec. 165 GRAIN CENTER BOMB DAMPS IN LESS THAN 15 msec.
-009	2.1 (CSM)	96.1	319 $\pm$ 2	1.60	STEEL	165 GRAIN SIDE BOMBED UNSTABLE AT 5000 cps (CSM).
-010 W/TUBE	5.3	91.8	319 $\pm$ 2	1.60	STEEL	INTERMEDIATE-FREQUENCY INSTABILITY (850 cps) CHANGES TO HIGH-FREQUENCY (7000 cps) at FS_1 + 2.80 $\pm$ 0.05 sec.
-011 W/TUBE	5.2	98.5	319 $\pm$ 2	1.61	STEEL	INTERMEDIATE-FREQUENCY INSTABILITY (850 cps) CHANGES TO HIGH-FREQUENCY (7000 cps) at FS_1 + 2.80 $\pm$ 0.05 sec.
-012 W/TUBE	5.3	73.4	319 $\pm$ 2	1.62	STEEL	INTERMEDIATE-FREQUENCY INSTABILITY (850 cps) THROUGHOUT TEST.
-013	1.0 (CSM)	98.4	319 $\pm$ 2	1.61	ABLATIVE	INTERMEDIATE-FREQUENCY INSTABILITY RECOVERS FROM ONE POP AT FS_1 + 1. HIGH-FREQUENCY INSTABILITY 7,000 cps (CSM) 0.03 sec LATER AT SECOND POP.
-014-1	1.0 (CSM)	98.9	319 $\pm$ 2	1.68	ABLATIVE	INTERMEDIATE-FREQUENCY INSTABILITY RECOVERS FROM ONE POP AND GOES INTO HIGH-FREQUENCY INSTABILITY LATER AT SECOND POP.
-014-2	1.0 (CSM)	99.0	319 $\pm$ 2	1.60	ABLATIVE	INTERMEDIATE-FREQUENCY INSTABILITY RECOVERS FROM ONE POP AND GOES INTO HIGH-FREQUENCY INSTABILITY LATER AT SECOND POP.

*SEE SECTION VI FOR DISCUSSION ON METHOD OF PREDICTING PERFORMANCE. PERFORMANCE CORRECTED TO NOMINAL CONDITIONS.

Figure 4. Test Summary

V, B, Phase II (cont.)

An analysis of test data shows that the insertion of the oxidizer channel cover plates may have provided additional system phase shift causing the intermediate frequency instability. Stabilizing devices to either reduce the gain or shift the phase are now being considered for the fuel feed system.

The high-frequency instability is of a complex combined mode which appears to be triggered by pops due to the intermediate frequency instability. It is planned to insert an acoustic resonator in the injector to damp the high-frequency instability.

VI. LIMITATIONS

The major limitation encountered on the IOS Program was the absence of firing test data obtained at simulated altitude conditions. The absence of these data makes it impossible to give a precise definition of the performance.

The technique used to calculate the IOS injector performance is identical to that used on the SPS Program; however, it involves the use of a constant or multiplier to extrapolate sea-level performance to altitude performance. Since SPS test history has demonstrated that each injector pattern has a slightly different constant, it is obvious that the use of factors obtained from SPS injectors for the IOS injector is not precise.

The SPS Mod II injector had a mixture ratio distribution similar to that of the IOS injector and therefore should be the most applicable. The use of this factor indicates an IOS vacuum I_s of approximately 321 sec with the $\varepsilon = 62.5$ nozzle extension.

The Mod IV injector has a different mixture ratio distribution and therefore should be less applicable; however, if in the interest of conservatism the extrapolation factor associated with the Mod IV pattern is utilized the indicated IOS I_s is 317 sec.

While the foregoing methods are inadequate with respect to making a precise quantitative altitude prediction, it has been proved that there is a definite increase in performance because comparison of IOS sea-level test performance with similar SPS data shows a vacuum I_s increase of approximately 4 sec in $\varepsilon = 1.65$ steel combustion chamber.

VII. APPLICATIONS FOR RESEARCH

A total of 129 single-orifice tests were conducted on the IOS contract. In general, excellent agreement was achieved between the preliminary analytical models and experimental data. The physical insight achieved through the development of the various analytical models has conceptually explained all observed hydraulic phenomena. For the contoured orifice injectors the hydraulic models developed are adequate to predict discharge coefficient within $\pm$ 1% and no additional orifice element work is required. However, additional research is required on sharp-edged orifices. The remaining areas of deficiency in the orifice models are discussed below.

It was shown that the interactions of cross velocity and static pressure drop through the orifice define the initial flow deviation angle into the orifice. The secondary flow characteristics are attenuated by increasing orifice L/D due to viscous effects. However, it has not yet been quantitatively determined how much length is required or at what rate the damping will occur. Asymmetrical flow effects upon contoured orifices are negligible because the absence of a flow detachment zone inhibits secondary flow characteristics. Nevertheless, if sharp-edged orifices are desired for use with non-negligible cross velocity or low static pressure drop, additional analytical development of the asymmetrical flow sharp-edged orifice model is required.

In the case of symmetrical flow (low cross velocity) in sharp-edged orifices, flow detachment at the exit was experienced for $L/D < 1$ and attached flow was achieved in some cases with L/D as low as 2. However, the minimum L/D requirement to assure either flow attachment or detachment is also dependent upon secondary factors such as impingement angle, fluid density and viscosity, orifice diameter and pressure drop and possibly other parameters. To fully evaluate the conditions required to achieve definite flow attachment in the short-to-moderate L/D range, additional analytical model development and empirical data will be required. Although tests were conducted in the IOS investigation at L/D's of 1, 2, 4 and 8, the data were inconclusive for defining the small differentials between plates because of slight inaccuracies in either measured orifice areas or differences in entrance condition. Thus, additional L/D investigation will require that the data be obtained from a single-orifice plate tested at successively shorter length.

VIII. SUGGESTED ADDITIONAL EFFORT

The following items are recommended as additional effort to the IOS Program.

A. Continuation of the IOS effort with emphasis placed upon the attainment of dynamic stability while maintaining high performance. (This effort is the goal of Contract NAS 9-8285, which was awarded at the completion of the IOS contract.)

B. The development of a capability to determine the altitude performance of SPS injectors more expeditiously. The two primary advantages to be realized from this improved capability are (1) the uncertainty attached to the performance values discussed in Section VI, Limitations would be removed, and (2) the information would be available to the designer early in the development phase of the program when it is of the most value. The only method of determining altitude performance now available is test firing at AEDC. This approach is not desirable for small development programs with limited hardware because of the relatively long turnaround time required.

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